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Project Operations
HYDROGRAPHIC SURVEYING

1. Purpose. This circular disseminates updated policies, revised accuracy standards, and technical procedures for hydrographic surveying, superseding portions of EM 1110-2-1003, Hydrographic Surveying. New technical guidance on the use and calibration of acoustic multibeam survey systems is provided.

2. Applicability. This circular is applicable to USACE commands having responsibility for performing or contracting hydrographic measurement, construction payment, or condition surveys on civil works navigation or flood control projects.

3. References.

a. ER 1130-2-520, Navigation and Dredging Operations and Maintenance Policies.

b. EM 1110-1-2909, Geospatial Data and Systems.

c. EM 1110-2-1003, Hydrographic Surveying.

4. Distribution. Approved for public release. Distribution is unlimited.

5. Background. Procedural guidance and accuracy standards for performing hydrographic surveys are contained in EM 1110-2-1003. Since this manual was last updated in 1993-1994, significant technological improvements have occurred in vessel positioning (Global Positioning System), depth measurement (shallow-water acoustic multibeam swath systems), and near real-time data acquisition, editing, and processing systems. This new technology has been rapidly acquired by USACE commands and has resulted in significantly improved data accuracy and reliability.

6. Policy. Mandatory use of EM 1110-2-1003 for dredging measurement and payment surveys is prescribed by ER 1130-2-520. The revised accuracy standards and related technical guidance

contained in this circular supersede applicable portions of EM 1110-2-1003.

7. Scope. The following appendices are attached to this circular.

a. Appendix A: Hydrographic Survey Accuracy Standards and Classifications. New survey classifications and accuracy performance standards have been developed for USACE work. These accuracy standards supersede those currently shown in EM 1110-2-1003.

b. Appendix B: Use of Acoustic Multibeam Survey Systems on Navigation, Flood Control, and Dredging Projects. This appendix disseminates policy for acquiring and using multibeam survey systems on Corps navigation and flood control projects, for design, construction, dredging measurement and payment, and project condition surveys. It replaces and updates EC 1130-2-205 that was first published on 1 July 1996 and expired on 30 June 1998.

c. Appendix C: Field Calibration Procedures and Quality Assurance Procedures for Acoustic Multibeam Survey Systems. This appendix describes current technical procedures for field calibration of acoustic multibeam systems. It contains recommended guidelines for quality control and quality assurance processes and allowable tolerances. Criteria contained in this appendix is guidance, not policy.

8. Proponency. This circular is issued jointly by the Operations Division and the Engineering and Construction Division, Directorate of Civil Works. The proponents for policy contained in this circular are CECW-OD (ATTN: Tom Verna) and CECW-EP (ATTN: Bill Bergen). Technical issues shall be addressed to CECW-EP (Bill Bergen) or CETEC-TD-G (Robert Mann). Comments, recommended changes, or waivers to this circular should be forwarded to CECW-EP. This circular may be reissued prior to its

expiration. Portions of policy contained in this circular will eventually be incorporated in reference 3a. Technical guidance will be incorporated into reference 3b when it is next published during FY 2000.

FOR THE COMMANDER:

3 Appendices
APP A - Hydrographic Survey Accuracy Standards and Classifications
APP B - Use of Acoustic Multibeam Survey Systems on Navigation, Flood Control, and Dredging Projects
APP C - Field Calibration Procedures and Quality Assurance Procedures for Acoustic Multibeam Survey Systems

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Appendix A
HYDROGRAPHIC SURVEY ACCURACY STANDARDS AND CLASSIFICATIONS

A-1. Purpose. This appendix contains revised survey classifications and technical performance standards for USACE hydrographic surveys. These classifications and standards supersede those currently shown in the 1994 edition of EM 1110-2-1003. Most of the standards and criteria contained in EM 1110-2-1003 were designed to support older analog depth recording fathometers; mechanical, visual, or microwave positioning; and manual data processing and drafting methods. Within the past five years most of these instruments and processes have been radically changed, requiring the updated standards herein.

A-2. Revised Survey Classifications.

a. Dredge Measurement and Payment Surveys (Class 1). The scope of Class 1 (Contract Payment Surveys) defined in EM 1110-2-1003 has been modified to include two distinct subcategories of payment surveys based on the characteristics of bottom conditions and the potential for navigation hazards in the project. These classifications, and related accuracy standards, are intended to correspond closely with recently revised international hydrographic surveying charting standards. Survey requirements, accuracy standards, and quality control procedures vary as a function of bottom type, as indicated in Tables A-1 and A-2.

(1) Hard Bottom Material and/or New Work. This category of dredge measurement, payment, and acceptance surveys includes dredging of newly authorized projects containing hard bottom material, such as rock or compacted material, or maintenance projects containing hard bottom material. All newly authorized projects are not necessarily in this category. This category may also include projects where low under-keel clearances are anticipated over potentially hazardous bottom conditions. Mechanical or acoustic sweep methods must be employed to insure 100% bottom coverage in order to detect small objects remaining above the required dredging prism. The most precise positioning and depth measurement standards and techniques must be employed for this class of project. In actuality, only a small number of Corps projects fall under this category--for example, projects like Kill Van Kull, NJ and St. Marys River, MI.

(2) Soft Bottom Material and/or Maintenance Dredging. This category of dredge payment surveys is intended to cover newly

authorized or maintenance dredging projects containing soft sand/silt bottoms not judged to be hazardous to vessel hulls; or in projects with soft, featureless, and relatively continuous channel bottoms where gaps in coverage between survey lines are unlikely to yield potential hazards/strikes. The vast majority of the Corps 926 navigation projects and 12,000 miles of maintained waterways fall within this category--e.g., inland and intracoastal navigation systems and most coastal harbor projects. Dredge measurement, payment, and acceptance surveys are typically performed by cross-section methods using single beam acoustic transducer systems. Acoustic multi-transducer or multibeam sweep systems may optionally be used if available.

(3) Underwater Hazard Investigation Surveys. Detailed investigation surveys of hazardous objects lying within the authorized prism or project depth should follow Class 1 survey accuracy and quality control standards. These surveys may also include precise investigation surveys of/around locks, dams, abutments, jetties, bulkheads, and other structures in a navigation project. If full bottom coverage and/or object detection sweeping is required, then the standards for the most precise (Hard Material category) of Class 1 surveys should be followed. On critical surveys, 200% acoustic coverage is recommended.

b. Project Condition Surveys (Class 2). The EM 1110-2-1003 definition of the types of surveys included within this category are unchanged; however, the accuracy standards and quality control criteria have been modified, as indicated in Tables A-1 and A-2.

c. Reconnaissance Surveys (Class 3). Reconnaissance survey accuracy and quality control standards currently defined in EM 1110-2-1003 are largely obsolete and have been revised under this circular. The purpose of these surveys (as defined in EM 1110-2-1003) is still unchanged--they represent an economical method of rapidly assessing the condition of a project. With LIDAR and multibeam acoustic technology, there is essentially no distinction between a Class 2 Project Condition Survey and a Class 3 Reconnaissance Survey.

A-3. <u>Revised Survey Accuracy Performance Standards</u>. Table A-1 contains revised performance standards for Corps hydrographic surveying, covering all survey classifications. These new standards supersede those shown in Table 2-1 (Maximum Allowable Errors for Hydrographic Surveys) of the current (1994) edition of

EM 1110-2-1003. These revised standards reflect current survey instrumentation, practices, and capabilities, whereas the standards and criteria in EM 1110-2-1003 are more representative of 10-year old hydrographic surveying technology--i.e., pre Global Positioning System and acoustic multibeam. In reality, position and depth accuracy criteria have not significantly changed: only the measurement statistic (95%) has been modified. These standards are considered "minimum technical performance standards" and are independent of the measurement process employed. In addition to performing standard survey quality control calibrations of system components, some form of accuracy performance (or quality assurance) test should be periodically performed to demonstrate and document that these accuracy standards are being achieved. In some instances, more rigid standards may need to be developed and followed to meet specific project requirements.

Table A-1. Accuracy Performance Standards for Corps of Engineers Hydrographic Surveys

	USACE SURVEY CLASSIFICATION			
	Class 1 Contract Payment Surveys (Dredge Measurement/Payment)		Class 2 Project Condition	Class 3 Recon
	Hard Mat'l	Soft Mat'l		
HORIZONTAL ACCURACY [1] (95% Confidence Level)	2 m (6 ft)	5 m (16 ft)	5 m (16 ft)	5 m (16 ft)
DEPTH ACCURACY (95% Confidence Level) [2]				
Mechanical (d<15 ft)	±0.25 ft	±0.25 ft	±0.5 ft	±1.0 ft
Acoustic (d<15 ft)	±0.5 ft	±0.5 ft	±1.0 ft	±1.0 ft
Acoustic (15>d<40 ft)	±1.0 ft	±1.0 ft	±2.0 ft	±2.0 ft
Acoustic (d>40 ft)	±1.0 ft	±2.0 ft	±2.0 ft	±3.0 ft
OBJECT DETECTION CAPABILITY (95% confidence)				
cubic dimension [3]	> 0.5 m	> 1 m	N/A	N/A
BASE CONTROL NETWORK ACCURACY				
Primary horizontal DGPS	USCG Radiobeacon DGPS System			
Supplemental horizontal [4]	3rd order, Class I (1:10,000)			
Vertical control [5]	3rd order			
FEATURE LOCATION ACCURACY (95% confidence)				
Topographic features	2 m (6 ft) [eg, bulkheads, dredging limits, etc]			
Fixed navigation aids	2 m (6 ft) [e.g., lighthouses, ranges, beacons]			
Floating navigation aids	10 m (30 ft)			

EXPLANATORY NOTES:

1 Horizontal accuracy standard is two dimensional radial (circular) error measured at 95% confidence region (2.447-F) accuracy, and is specified for the plotted elevation relative to the local geodetic framework. It includes all propagated error components that make up the overall position error budget (i.e., geodetic network accuracy, electronic positioning system/DGPS accuracy, dynamic-latency/roll/pitch/heave errors, antenna-transducer-beam forming errors, etc.). Nationwide code phase DGPS networks should generally achieve this specified accuracy at reasonable distances from the reference station; however, in some cases, carrier-phase DGPS positioning may be necessary. Project units will determine use of either English or Metric standard.
2 Elevation accuracy performance standard is evaluated at 95% confidence level (1.96-F) and is specified for reduced depth, relative to a local reference datum. It includes all propagated error components that make up a reduced elevation (i.e., local geodetic datum errors, tide/stage modeling-extrapolation-interpretation errors, dynamic-latency/roll/pitch/heave errors, acoustic measurement errors, including velocity & refraction & beam forming errors, etc.). In areas with uncertain datum reference planes, undefined tidal modeling, or subject to large hydraulic grade or weather induced water surface anomalies, centimeter-level carrier-phase DGPS positioning may be necessary to achieve this accuracy requirement. Accuracy standard is applicable only for project depths less than 80 feet or 25 m. The variable accuracy tolerances account for differing project conditions found on USACE navigation projects (e.g., inland, coastal/tidal, depth, measurement methods, etc.). Mechanical depth measurement methods in less than 15 feet of water include: lead line, differential leveling, total station, etc. Acoustic methods include single, multiple, or multibeam. Project depths less than 15 feet are intended to include shallow draft or inland navigation projects where tide/stage and sea state corrections are minimal. Depths over 40 feet are intended to include coastal entrance channels or other offshore areas subject to significant tidal phase, tidal range, and sea state variations.
3 Performance standard is based on detection of object of cubic side dimensions indicated, using either mechanical or acoustic sweeping/scanning methods. Demonstration testing may be specified/required on critical projects. Reference Appendix B, Section B-3c.
4 Required to control traditional tag line or range-azimuth surveys of areas where DGPS is obscured.
5 Required to transfer elevations to supplemental gages or staffs.

A-4. Quality Control Criteria. Table A-2 contains some of the more critical quality control criteria recommended for USACE hydrographic surveys. Other supplemental quality control calibrations required for individual system components are described in Appendices B and C and EM 1110-2-1003. Some of the general quality control and related criteria shown in Chapter 3 of EM 1110-2-1003 are superseded by Table A-2. The quality control criteria indicated in Table A-2 are based on generally accepted procedures currently in practice. However, these criteria are not to be considered as rigid or absolute prescriptive standards. These criteria may be locally modified on individual survey platforms as long as independent quality assurance testing demonstrates the required accuracy or object detection performance standard in Table A-1 is being achieved. This is consistent with Corps policy to minimize use of prescriptive surveying requirements and criteria--see Chapter 11 in reference 3c (Accuracy Standards for Engineering, Construction, and Facility Management Surveying and Mapping).

Table A-2. Recommended Quality Control Criteria for Corps of Engineers Hydrographic Surveys

	USACE SURVEY CLASSIFICATION			
	Class 1 Contract Payment Surveys (Dredge Measurement/Payment)		Class 2 Project Condition	Class 3 Recon
	Hard Mat'l	Soft Mat'l		
SURVEY DENSITY				
Cross Section Spacing	100% sweep[1]	NTE 200 ft [2] (NTE 60 m)	NTE 500 ft[3] (NTE 150 m)	as reqd[4]
SINGLE-BEAM QUALITY CONTROL				
Velocity/bar calib	> 2/day	2/day	1/day	1/project
Cross-line check	Required	Optional [5]	Not reqd	Not reqd
MULTIBEAM QUALITY CONTROL [6]				
Max beam angle[7]	90-degrees	120-degrees	Unlimited	Unlimited
Beam overlap [8]	10%-50%	10%	N/A	N/A
Velocity calib	> 2/day	2/day	2/day	1/day
Bar check (center)	2/day	2/day	1/day	Optional
Alignment calib	as reqd	as reqd	as reqd	as reqd
Patch tests calib	periodic	periodic	periodic	periodic
Performance test	1/project	1/project	3 months	3 months
VOLUME COMP METHOD [9]	DTM/DEM	TIN or AEA	TIN or AEA	N/A
POSITION CALIBRATION [10]	1/day	1/project	1/project	1/project
MAXIMUM SURVEY SPEED [11]	5 knots	10 knots	Unlimited	Unlimited
ACOUSTIC FREQUENCY [12]	[200 KHz Nominal]		[200 KHz Nominal]	

EXPLANATORY NOTES:

1 Full bottom coverage may be obtained using any of the following methods: mechanical bar sweep, multi-transducer acoustic sweep, acoustic multibeam sweep, or side-scan sonar sweep.
2 Standard is specified for single-beam echo sounder, cross-sections run perpendicular to channel alignment. 100-foot sections are recommended for

most dredging projects. If longitudinal sections are run, additional sections are required along channel side slopes, per EM 1110-2-1003. Full coverage acoustic sweep systems may be used; however, such coverage is optional for these projects.
3 Standard specified for single-beam echo sounder, cross-sections run either perpendicular to or longitudinal with channel alignment. Side slope coverage optional. Full coverage LIDAR or acoustic sweep systems may optionally be used if available.
4 Any single transducer line spacing may be used that sufficiently details the channel or project area (e.g., single centerline or quarter lines). Full coverage LIDAR or acoustic sweep systems may optionally be used if available.

5 When single beam transducer cross-sections are run, cross-check lines may optionally be run and statistically compared with the primary survey lines--see EM 1110-2-1003.
6 Multibeam component calibrations and accuracy performance tests must be performed and documented for all surveys--see Appendix C for details and recommended tolerances. Accuracy performance tests are recommended at beginning of all critical dredging projects, or occasionally on surveys within a project where high quality assurance is required. Depending on documented stability of system, frequency of calibrations and performance tests may be locally modified from the indicated intervals.
7 Beam/swath width should generally not exceed the indicated values, unless independent accuracy performance test results indicate depth accuracies can be achieved with wider arrays. The beam angle should be reduced for critical object detection or should performance test results indicate poor correlation in the outermost portion of the array. Larger beam widths must be recorded to compensate for roll.
8 50% side overlap (i.e., 200% bottom coverage) is recommended when sweeping for rock shards or other hazardous objects remaining above project grade. Beam angle should not generally exceed 90 degrees in strike detection work--due to expansion and poorer return from outer beams.
9 Refer to Appendix B (Section B-3f) for dredge volume computational criteria using digital terrain models (DTM), digital elevation models (DEM), triangulated irregular network (TIN) models, and average end area (AEA) computations.
10 Criteria is for local or regional code or carrier phase DGPS positioning system, requiring position verification (i.e., blunder) check; either at known project control point or from redundant USCG beacon positions.
11 Further limitations may be required for multibeam systems to insure 100% or greater forward (along-track) coverage.
12 200 KHz (single beam or multibeam) is a recommended standard for most Corps navigation projects. Higher frequencies (i.e., up to 500 KHz) may be specified/used on hard bottoms or for detailed site investigation work, and lower frequencies (i.e., down to 12 KHz) may be recommended in projects containing unconsolidated sediments/fluff. Reference EM 1110-2-1003.

Appendix B
USE OF ACOUSTIC MULTIBEAM SURVEY SYSTEMS ON NAVIGATION, FLOOD CONTROL, AND DREDGING PROJECTS

B-1. Purpose. This appendix disseminates policy for acquiring and using single transducer, shallow-water multibeam survey systems on Corps navigation and flood control projects. It updates EC 1130-2-205 that was first published on 1 July 1996 and expired on 30 June 1998.

B-2. Background. Shallow water multibeam survey systems use a single transducer or pair of transducers to form a fan array of narrow beams that result in acoustic travel-time measurements over a swath that varies with system-type and bottom depth--typically mapping an area 2 to 14 times the channel depth with each array pulse. Multibeam systems can obtain 100% bottom coverage. Multibeam systems can also be configured for waters-edge to waters-edge coverage (i.e., over 180 degree swath), allowing side-looking, full-coverage underwater topographic mapping of constricted channels, lock chambers, revetments, breakwaters, and other underwater structures. Some systems collect acoustic backscatter information and thus produce digital side-scan imagery simultaneously with the swath mapping data, an advantage in locating underwater rock, hazards, or other objects (strike detection). Multibeam acoustic frequencies and signal processing methods may be adjusted to match the survey requirements--dredging measurement and payment, strike detection, structure mapping, etc. Some systems can provide near real-time data collection, filtering, editing, quality assessment, and display; along with near real-time (i.e., on board) data processing, plotting, and volume computations; thus, final plan drawings, 3D terrain models, and dredged quantities can be completed in the field the same day the survey is performed. Multibeam systems have technically advanced since their introduction in the early 1990's to the point that they now have a direct application to most Corps navigation project survey activities. When properly deployed and operated, the accuracy, coverage, and strike detection capabilities of multibeam systems now exceeds that of traditional vertical echo sounding methods.

B-3. Policy.

a. Measurement & Payment Surveys. Multibeam swath survey systems that provide complete bottom coverage are recommended for use in dredging measurement and payment surveys, i.e., plans & specifications surveys, pre-dredge surveys, post-dredge surveys, and final acceptance/clearance surveys. Multibeam systems are an effective quality control process on dredging projects requiring 100% bottom coverage to assess and certify project clearance. They may optionally be used on dredging projects where less than 100% bottom coverage is required. Refer to Appendix A for recommended bottom coverage and quality control requirements for various types of dredging or surveying projects.

b. Project Condition Surveys. Multibeam survey systems may optionally be used for project condition surveys of channels, revetments, and other underwater structures where complete bottom coverage is desired to fully delineate the feature or structure.

c. Strike Detection. Multibeam survey systems represent an effective mechanism for detection of rocks, wrecks, debris, or other navigation hazards lying above grade in a navigation channel. The side-looking aspects of both the multibeam signal and the digital side-scan sonar imagery signal may be used for such investigation purposes. In order to enhance the probability of detection, and depending on documented system performance characteristics, 200% bottom coverage may be specified in order to insure objects are ensonified from two aspects. Performance demonstration tests on simulated objects should be periodically performed to assure data detection quality and assess the need for overlapping coverage.

d. Emergency Operations. Multibeam systems recording both topographic data and digital side-scan imagery are recommended for locating underwater objects and marking objects for clearing after natural disasters.

e. Other Channel Sweeping Methods. Multiple-transducer, boom-mounted, channel sweep systems are generally preferred for use over multibeam survey systems in shallow-draft (<10 feet), sand/silt-bottomed navigation channels. Multi-transducer systems will also provide 100% bottom coverage on navigation channels, as will mechanical, or manual, channel sweeping techniques and side scan sonar devices. Mechanical bar sweeps remain an effective dredging quality control technique when rock is encountered.

f. Volume Computations. Measurement and payment surveys performed using either multibeam or multiple transducer boom systems shall compute pay quantities using the full, densely populated, data digital terrain models (DTM) generated by swath survey data. Data sets should be thinned to a gridded digital elevation model (DEM) only when multiple or duplicate points within a specified bin size exist; the representative depth selected within a fixed bin should not be biased or overly smoothed. The bin (or DEM post) size should not exceed either the estimated positional accuracy or the acoustic beam footprint size. The algorithms used for data thinning routines must be thoroughly tested to verify thinned quantities do not differ from raw data set quantities. In effect, data thinning shall be kept to an absolute minimum. Actual dredged quantities should be computed from either the raw DTM or the gridded DEM relative to the applicable payment template using standard CADD software routines. (For sparse data sets, such as traditional single-beam cross-section surveys, dredged volumes may be computed using traditional average end area routines or from triangulated irregular network (TIN) models).

g. Dredging Contract Specifications. Measurement and payment provisions in dredging contract specifications shall clearly stipulate the type of survey system, acoustic frequency, navigation guidance system and software, data acquisition parameters (horizontal and vertical control, density, etc.), data processing and binning techniques, and mathematical volume computational method/software that will be employed by the Government. In order to insure consistency when performing measurement and payment surveys, commercially available software should be employed for data collection, data processing, data quality control, and volume computations.

h. Calibration and Quality Control. Field calibration of multibeam acoustic refractions and vessel motion is significantly more critical and complicated than that required for standard single beam systems. Recommended calibration requirements, procedures, and allowable tolerances are contained in Appendices A and C. Accuracy performance tests are essential in order to demonstrate data quality. These quality control calibrations and quality assurance performance tests must be processed and adjusted on board the survey vessel prior to and during the survey--after-the-fact checks in the district office are of little value. This implies that a near real-time field-finish data collection, processing, editing, and plot creation process must be established in the field in order to insure the most cost effective utilization of this technology.

i. Training Requirements. Multibeam system operators require considerable expertise in both surveying and on CADD work stations. Prior to using multibeam systems on USACE surveys, system operators should have completed specialized training.

Presently, the Corps PROSPECT course on Hydrographic Surveying Techniques is not sufficient for multibeam training. Comprehensive training courses are available from: (1) the University of New Brunswick, (2) Coastal Oceanographics, Inc., (3) Triton Elics International, (4) Odom Hydrographic Systems, Inc., or (5) The Hydrographic Society of America seminars. Multibeam manufacturers may also offer specialized training sessions. In addition, the operator should have completed a manufacturer or Corps PROSPECT course associated with the differential GPS system, inertial compensating system, and CADD processing/editing system employed. For contracted multibeam survey services, the Architect-Engineer (A-E) contract solicitations shall require that proposals identify the experience and training of system operators in Block 7 of the SF 255.

j. Floating Plant. Multibeam systems are normally more cost-effectively utilized on small, mobile (trailerable) survey vessels up to 28 feet in length, with the transducer assembly externally mounted over the side (bow, port, or starboard). Permanent placement on large, non-trailerable, 30 to 65 foot survey vessels is generally recommended only in areas where such a vessel is permanently deployed on a major navigation project.

k. Plant Utilization and Justification. Multibeam surveys may be obtained using hired-labor forces or through A-E service contracts. Commands proposing to purchase multibeam systems shall obtain advance approval from HQUSACE (ATTN: CECW-OD). This approval is necessary to ensure effective and efficient utilization of floating plant, given the $200 K to $500 K investment for a multibeam system. Justifications shall indicate the (1) proposed vessel, (2) system configuration (hardware and software), (3) estimated annual utilization (time and location), (4) FTE allocations, (4) system operator qualifications, (5) field data processing, editing, and plotting, and turnaround capabilities, (6) estimated daily plant and survey crew rental rate, and (7) comparative analyses between hired-labor and contract costs.

l. Data Collection Hardware/Software. Navigation, data collection, and data processing software employed with multibeam systems shall have real-time guidance, display, and quality assurance assessment capabilities. The software shall also be capable of applying all calibrations and corrections in the field such that data can be collected, edited, and processed in near real-time in order to effectively support dredging contract administration. Software shall also be capable of performing near real-time statistical quality assurance assessments between comparative accuracy performance test models. Strike detection systems may require more high-end PC-based or CADD work stations in order to adequately display and replay 3D imagery in real-time. CADD data thinning or binning routines shall be rigorously tested to ensure data integrity is not adversely modified. This may be accomplished by comparing quantities between raw and thinned data sets.

m. Vessel Positioning Requirements. In general, code-phase, meter-level US Coast Guard differential GPS radio beacons will provide sufficient accuracy for most project surveying applications. It also insures Corps projects are referenced relative to the National Spatial Reference System (NSRS). Where required, translations from NAD 83 to NAD 27 should be performed real-time by the hydrographic data acquisition software. In offshore coastal areas where traditional tidal modeling is deficient, carrier-phase kinematic DGPS (either real-time kinematic (RTK) "OTF" or post-processed) may be needed to enhance vertical accuracy of measured depths. When the multibeam is deployed horizontally to map underwater structures, RTK carrier-phase DGPS may be needed to maintain decimeter-level horizontal accuracy.

Appendix C
FIELD CALIBRATION AND QUALITY ASSURANCE PROCEDURES FOR ACOUSTIC MULTIBEAM SYSTEMS

C-1. Purpose. This appendix provides recommended technical guidance for performing quality control calibrations and quality assurance tests of multibeam sonar systems used on Corps navigation projects.

C-2. References.

a. Field Procedures for the Calibration of Shallow Water Multibeam Echo-Sounding Systems, André Godin, Canadian Hydrographic Service, February 1996.

b. HYPACK User's Manual, Coastal Oceanographics, Inc., 1998.

c. Multibeam Surveying Workshop Proceedings, U.S. Army Corps of Engineers and NOAA Surveying, Mapping, and Remote Sensing Conference, St. Louis, MO, 19 Aug 1997.

C-3. Background. Field calibration requirements for multibeam systems are significantly more difficult and demanding than those required for single beam echo sounders. Periodic, precise calibration is absolutely essential in order to assure multibeam derived elevations meet the prescribed accuracy tolerances for the project--especially at the outer beams of the array where refractive ray bending and vessel alignment and motion variations can significantly degrade the data quality. Multibeam system sensor alignments and measurement corrections must be periodically aligned, calibrated, tested, and monitored in order to insure data quality. Procedures for performing these calibration and quality control processes are detailed in the referenced publications, and in the manuals provided with the individual sensors making up a multibeam survey system.

a. At present, USACE districts have acquired two different types of multibeam transducers - the Reson Seabat and the Odom Echoscan multibeam systems. In addition, the most commonly used navigation, data acquisition, calibration, and editing software are HYPACK (Coastal Oceanographics, Inc.--reference C-2b) and Triton Elics (TEI) Bathy Pro. This appendix describes the calibration procedures currently employed for these these multibeam systems and software packages; in conjunction with methods developed by the Canadian Hydrographic Service (CHS) and University of New Brunswick. Other multibeam systems, such as Simrad EM3000, Simrad EM950, Atlas STN Fansweep 20 or 15, and Elac Bottomchart Compact, may need other calibration procedures.

b. It should be strongly emphasized that the software and procedures for calibrating, editing, and thinning multibeam data are still being refined and will undergo modifications as new data is acquired and performance is validated. Likewise, the overall accuracy and object detection performance capabilities of multibeam systems are still being assessed. Therefore, any recommended procedures outlined in this appendix must be considered as interim.

C-4. Multibeam Calibration, Quality Control, and Quality Assurance Requirements. There are distinct calibration, QC, and QA procedures that must be performed in order to effectively operate a multibeam system. These include acoustic refraction measurements (i.e., velocity casts and bar checks), system latency calibrations (time variances between positioning, depth, and motion sensors), vessel motion sensor calibration (roll, pitch, and heave sensors), and various other vessel alignment and coordinate/datum corrections. Some calibrations are performed during initial equipment installation on the vessel; however, others must be performed on a more frequent basis--especially when dredging measurement and payment surveys are involved. A summary of measurement and calibration requirements is contained in Table C-1 at the end of this appendix. Failure to perform adequate calibration may render a survey invalid. The following breakdown of calibration tests is taken primarily from Godin (reference C-2a) and HYPACK (reference C-2b) manuals.

a. Sensor Alignment and Offset Measurements. Alignment and offset parameters must be measured for the various sensors making up the multibeam system, e.g., gyro alignment/offsets, transducer mounting angles/offsets, DGPS antenna offsets, static and dynamic drafts, vessel settlement/squat, and estimated latencies. These measurements are made upon initial installation or upon replacement, removal & reinstallation of a sensor. Alignment and offset corrections are typically entered in the software system setup modules--e.g., HYPACK Device Setup or Triton Isis Sonar Setup.

b. Patch Tests/Residual Bias Calibration. Patch Tests are performed after initial installation, and periodically thereafter if sensors are modified, to quantify any residual biases from the initial system alignment. During this calibration series, four separate tests are performed to determine residual alignment biases for:

- Position Time Delay (Latency)
- Pitch Offset
- Roll Offset
- Yaw/Azimuthal Offset

The above parameters are tested, quantified, and updated using commercial software Patch Test routines.

c. Bar Checks. Traditional bar checks under the center beam must be performed to quantify any draft or index errors in the system.

d. Velocity Profile Corrections. Sound velocity profile calibrations are critical--in particular for the outer portion of the beam array. Velocity calibrations shall be performed periodically during the day, and no less than twice per day, and at more frequent intervals or locations in a project if physical changes in the water column (e.g., temperature, salinity) are impacting data quality. The quality of velocity data may be subsequently assessed through use of the "Performance Test" which compares overlapping survey data models. Beam angles shall be reduced below the maximum limits specified in Appendix A if velocity data and/or performance tests indicate uncertainty in outer beam depth measurements. Velocity profile data is entered into the system such as under the HYPACK Sound Velocity Program section.

e. Quality Assurance Performance Test. A performance test is a quasi-independent test used to assess the quality of data being collected, and to verify conformance with the prescribed accuracy specification or object detection requirements for the project. A performance test typically compares overlapping data sets from two different multibeam surveys. This test could also be performed by comparing multibeam data with that collected by another single beam echo sounder. Other comparison test methods are also used, such as matching multibeam bathymetry of a flooded Corps lock chamber against topographic data measured in the same lock chamber during a dewatered state. Object detection capabilities should also be verified by sweeping over simulated objects of known size; placed either in open water or controlled lock chambers. These tests should be periodically performed as a QA check on the overall system performance. A performance test failure indicates the system parameter alignments, offsets, or velocity profiles are invalid, and must be retested. Performance data reduction, processing, and statistical analysis should be performed in near real-time--preferably on board the survey boat. They should be conducted before a critical dredging measurement and payment survey project; however, they are not needed prior to individual surveys in that project. The frequency which performance tests are conducted is a function of past system performance, as evaluated by the field system operator. Therefore, no rigid guidance is prescribed--performance tests may be required weekly, monthly, quarterly, or less frequently, depending on the long-term stability of the results, variations in different project areas, etc. See Table C-1 for recommended allowable tolerances.

f. Real-Time Quality Assurance Tests. This simply involves operator assessment of data quality as it is being collected, making visual observations of cross-track swaths (i.e., noting convex, concave, or skewed returns in flat, smooth bottoms), data quality flags/alarms, or noting comparisons between adjacent overlapping swaths or between independent single beams. Real-time software must have features that allow some form(s) of real-time quality assurance assessment, and performing immediate corrective actions. An alternative quality control assessment is a traditional bar check of individual beams--see reference C-3c.

g. Criteria. Table C-1 contains recommended minimum requirements and tolerances for each of the above tests. Since many of the alignment and offset parameters are interrelated, failures at one level of test may require recalibration and/or retesting prior levels. The remaining sections in this appendix provide more detail on technical procedures for performing the individual tests. The referenced publications or manufacturer's operation manuals should be consulted for more details.

C-5. Coverage of Multibeam Systems. The coverage of multibeam systems is a function of swath width and water depth. Most systems provide coverage of two to approximately seven times the water depth. The number of individual beams (and footprint size) within the swath array varies with the manufacturer. The outer beams on each side of the swath are subject to more corrections and may not be useful. The maximum angular extent of coverage must be verified, and accordingly restricted, by conducting some form of independent performance test. Due to the increased density of soundings with multibeam systems, it is possible, with proper calibration and adjustments, to detect and resolve smaller objects on the bottom relative to single beam systems. However, this detection capability may be reduced due to larger footprints in the outer beams.

C-6. Error Sources in Multibeam Systems. Several sources of errors and biases exist in multibeam surveying which are not found in single beam surveying. With improved resolution and coverage comes the need for much greater control and calibration to ensure that the sounding is recorded from the correct position on the sea floor. This is accomplished by using a high accuracy differential GPS system, heave-pitch-roll (HPR) sensor, and a gyrocompass. In addition, the time synchronization for all these components is critical. For this reason, the system accuracy is comprised not only of the multibeam sonar accuracy but also these various components which make up the total system. Some of the more significant error components include:

a. Static offsets of the sensors. These are the distances between the sensors and the reference point of the vessel or the positioning antenna.

b. Transducer draft. This is the depth of the transducer head below the waterline of the vessel. As in single beam systems, standard bar checks are performed to measure static and dynamic draft variations.

c. Time delay between the positioning system, sonar measurement, and HPR sensor. This delay or latency must be accurately known and accounted for in the processing of the hydrographic data.

d. Sound velocity measurements. The velocity of sound in the water column must be accurately known so the correct depth can be measured.

e. The acceleration and translation measurements of the HPR. These measurements are critical for corrections to the vessel's roll and pitch.

These parameters must be measured and corrected in the multibeam sonar system. These corrections must be performed in the field, not in a post-processing environment. Commercially available software is designed to process and accommodate these inputs, offsets, and corrections.

C-7. Initial Installation Alignment and Static Offset Measurements. This is the process of physical measurement and alignment of the vessel platform, transducers, gyrocompass, and HPR sensor. This measurement should be performed with the vessel stabilized on a trailer or on blocks where more exact measurements can be made. This will minimize errors in positioning of the sensors and, with the proper offsets applied, the static corrections will be reduced. The sensors should be measured from a reference point in the vessel. This point is typically the center of gravity or the intersection of the pitch and roll axis. The center of gravity will change with varying load conditions of the vessel and thus must be chosen to represent the typical conditions while surveying. On large stable vessels, the center of gravity will slightly change vertically along an axis that contains the center of buoyancy. On smaller vessels, the center of gravity and the center of buoyancy may not be exactly aligned due to eccentric loading. This condition is to be avoided as it also contributes to the instability of the vessel itself. This information can be obtained from the blueprints of the vessel. This reference point (now the coordinate system origin) should be a place which is easily accessible and from where measurements to the sensors will be made. The coordinate system should be aligned with the x-axis along the vessel keel, the y-axis abeam the keel, and the vertical (z-axis) positive up. The offsets of the sensors are measured from the reference point to the center of the sensor. The center of the sensor can be found in the manufacturer's schematic of the sensor or can be accurately measured with a survey tape. It is common for the acoustic and physical centers to be in different places (e.g., Simrad EM 3000). The magnitude and direction of the measurement should be verified and recorded.

a. HPR Sensor. If possible, the HPR sensor should be placed on the centerline of the vessel as close as possible to the center of gravity or the intersection of the roll and pitch axes of the vessel. (The TSS DMS-05 allows heave high pass filtering at a remote location). If possible, use the same mount angles as used for the transducer. The x-axis of the HPR should match the x-axis of the transducer. Azimuthal misalignment of the HPR will result in the depth measurements being in error proportional to the water depth. Misalignment of the HPR sensor in yaw causes a roll error when pitching, and a pitch error while rolling. (If the transducer and HPR are collocated (e.g., Odom Echoscan), many alignment corrections become far less critical).

b. Transducer. The multibeam transducer should be installed as near as possible to the centerline of the vessel and level about the roll axis. It should also be aligned with the azimuth of the vessel. This alignment is critical since there is no beam steering with either the Reson Seabat or Odom Echoscan. There is, however, beam steering with the Simrad transducers about the y-axis. (The EM 950/1000 is steered in roll, EM 3000 is steered in pitch, and the EM 300 is steered in roll-pitch-yaw).

(1) Most multibeam transducers used on smaller USACE vessels are mounted over-the-side on a shaft and boom device. (Norfolk and New York Districts 65-foot vessels have hull-mounted transducers). With this type of mount, it is imperative that the azimuthal alignment between the transducer and keel be as accurate as possible. This can be accomplished with the vessel on a trailer or blocks on land and using standard surveying and leveling techniques. Since this boom mounted technique allows for raising the transducer at the end of each day of operations and lowering it at the start of the next day’s survey, this type of mount should be periodically checked for correct alignment. The frequency with which it is checked will depend on what type of surveying is performed and under what conditions. Hull mounted transducers are generally fixed in place and will not need to be checked as frequently.

(2) The angle of the transducer mount must be determined and recorded, unless the HPR is collocated. Since most vessels underway will be lower in the stern, the transducer will generally need to be rotated aft to compensate for this angle. The patch test will also check for the transducer angle. The resulting beam should then project normal to the sea floor while conducting surveying operations.

c. Gyro. The gyro should be aligned with the x-axis of the vessel using an electronic total station and geodetic control points. This can be done with the vessel on a trailer or secured tightly against a pier where there is minimal wave action. The gyro should be warmed up and, if necessary, the proper corrections for latitude applied. Locate two points on the centerline of the vessel and position a target on each of them. Observe the two targets with the total station and synchronize the readings with the gyro readings. Several readings will be needed for redundancy. Compute the vessel’s azimuth and compare with the gyro readings. Compute the mean and standard deviation of the readings. If the offset is more than 1° at the 95%

confidence level, realign the gyro with the centerline and repeat the observations. If less than 1°, apply the correction to the gyro output. This procedure can also be performed using three GPS receivers instead of the total station. The processing may take longer than with the total station.

d. Squat/Settlement Measurement using Transit/Theodolite. The combined squat and settlement of the vessel should be measured at several speeds and a look-up table produced for correcting the transducer draft. This measurement is essential since the HPR will not measure the long-term change in elevation. The sensor will record the sudden change in elevation but the measured heave will drift back to zero. The settlement can be measured with a transit on shore and a 2- meter level rod or stadia board on the vessel positioned over the HPR sensor (i.e., the point where the heave data are low pass filtered). The vessel should make several passes at various speeds in front of the shore station and the rod elevation recorded. The elevation difference at each speed is noted and used as the draft correction while surveying. Be sure the correct sign is applied when entering the correction in the software.

e. Squat/Settlement Measurement using GPS . An alternate method for determining squat/settlement makes use of carrier-phase differential GPS elevation difference measurement.

(1) Position the DGPS antenna near the center of the vessel and measure the vertical and horizontal distance from the antenna to the vessel’s reference point with steel tape.

(2) Use data from a nearby tide gauge to provide a datum from which to measure the elevation. The gauge should be in the survey area and if the area is large, two gauges should be used.

(3) Run the same survey line at different speeds. Also run the line under different loading conditions.

(4) Record the GPS positions, heave, pitch, roll, vessel speed and water levels at common times. The sampling rate should be at the highest for GPS and HPR sensors (10Hz and 100Hz, respectively) while the water levels can be recorded at approximately 5-10 minute intervals.

(5) Record the antenna height while stationary.

(6) All data should be synchronized and interpolated if necessary.

(7) Use the GPS antenna offsets and attitude data to compute the roll and heave and correct the antenna elevations. Subtract water level data and heave data from GPS antenna elevation.

(8) With these corrections for motion and water levels, compute the average speed in the water and the average antenna elevation with respect to the ellipsoid. Produce a look up table for the transducer draft correction.

Differential GPS may be used to directly reference the absolute vertical position of the multibeam transducer, thus eliminating the need for tide/stage data, squat, dynamic draft, etc. See EM 1110-2-1003.

f. HPR Sensor Time Delay. Time delay in the attitude sensor will result in roll errors, which greatly affect reduced elevations at the outer beams. In addition, horizontal accelerations in cornering can also affect the HPR measurements, which will also result in errors in the depth measurements. Basically, the principle to detect roll errors is to observe, from the bathymetric data, short period changes in the across track slope of the sea floor when surveying flat and smooth areas. Coastal Oceanographic’s HYPACK and TEI's Isis/Bathy Pro programs can be used to check the time delay. HYPACK will process the timing in post-time while the TEI Isis/Bathy Pro displays a real-time confidence check. The Canadian Hydrographic Service and University of New Brunswick have developed UNIX based software to assess time delay in swath data.

g. Positioning Time Delay (Latency). Time delay in the positioning is the time lag between the time positioning data are received and the time the computed position reaches the logging module. This results in a negative along-track displacement of the depth measurements. While surveying at slow speeds, this displacement will be small. In general, the processing time for the position will vary with the number of observations used in the final GPS solution. If the time imbedded in the GPS message will be used, then you must ensure the correct synchronization between this time and the transducer or signal processing clock.

C-8. Patch Test (Residual Bias Calibration). Patch Tests are periodically performed to quantify any residual biases in the initial alignment measurements described previously. This test (actually a series of reciprocal lines run at varying speeds, depths, and bottom terrain) must be performed carefully to ensure that subsequent data collected when surveying is accurate and reliable. The Patch Test determines (and provide correctors for) the following potential biases: (1) residual pitch offset, (2) residual roll offset, (3) residual positioning time delay, and (4) residual azimuthal (yaw) offset. The determined offsets and delays will be used to correct the initial misalignments and calibrate the system. Each of these bias tests is described below and is summarized in Table C-2 at the end of this appendix.

a. Data Acquisition. Survey quality DGPS positioning instruments must be used when conducting the Patch Tests--especially in shallow draft projects. The weather should be calm to ensure good bottom detection and minimal vessel motions. Since most of the lines to be run will be reciprocal lines, it is important to have capable vessel steering and handling. The lines should be run in water depths comparable to the typical project depths encountered. The order the lines are run is not important although it is recommended that at least two (2) sets of reciprocal lines be run for redundancy. Although the outer beams of multibeam sonar are subject to a smaller grazing angle, these beams should provide good data provided the appropriate corrections are applied from the patch test. Vessel speed should be regulated such that 50% forward overlap is obtained. The maximum speed may be calculated by the following equation:

$$v = S * d * \tan(b/2) \qquad \text{Eq. C-1}$$

where:
- v = maximum velocity (m/s)
- S = sounder sampling rate per second (1/t)
- d = depth
- b = fore-and-aft beamwidth angle

b. Positioning Time Delay Test and Pitch Bias Test. Two or more pairs of reciprocal lines are run at different speeds to check for biases in both positioning time delay (latency) and pitch bias. Latency is determined from runs made over the same line in the same direction, but at differing speeds. (Both these biases may exist simultaneously and must be discerned and separated during the test data processing). These lines should be run in an area with a smooth, steep slope--10° to 20°, if possible. The slope should ideally be at least 200 m long in order to obtain good samples. A channel side slope may have to suffice if no other relief is available . At least two pairs of reciprocal lines should be run both up and down slope, at velocities differing by at least 5 knots to best assess the time delay. Pitch is determined from the runs made over the same lines at the same speed in opposite directions.

c. Roll Bias Test. In an area of flat topography, run at least one pair of reciprocal lines approximately 200 m in length to test for roll biases. Roll bias will best show up in deep water. Depending on the type of multibeam system, these lines should be run at a speed to ensure significant forward overlap of the beam's footprint. The beam width can be found in the manufacturer’s specifications.

d. Azimuthal (Yaw) Offset Test. Two adjacent parallel pairs of reciprocal lines shall be run normal to a prominent bathymetric feature such as a shoal or channel side slope, in shallow water. Do not use a feature with sharp edges such as wrecks since there is more ambiguity in the interpretation. The adjacent lines have an overlap of about 15% and the feature should be wide enough to ensure adequate sampling. This width is generally greater than three swath widths. These lines should be run at a speed to ensure significant overlap of the beam forward footprint--use the same equation as that for roll bias.

C-9. <u>Patch Test Data Processing and Adjustment</u>. Commercial Patch Test routines automatically calculate system latencies, roll, pitch, and yaw biases in multibeam data. HYPACK routines will grid the data into 100 cells before any adjustments are made; however, the reduced data set may not be accurately representative of the test lines. The procedure followed by TEI and CHS/UNB uses the entire data set collected from the patch test lines without thinning (i.e., gridding or binning). The reason for this difference is due to the processing speeds of the platforms used (PC vrs. UNIX workstation). Visualization of the bathymetric data is important in both methods. In addition, the position and attitude data should be checked for errors, especially noting the time tag errors. Cleaning of the bathymetry is not necessary since individual soundings will not be adjusted but rather clusters of data points will be analyzed. The procedures to process the Patch Test data should follow the CHS/UNB sequence recommended below. Note that this differs from the sequence recommended by HYPACK: roll-latency-pitch-yaw.

a. Positioning Time Delay (Latency) Bias. This delay is computed by measuring the along-track displacement of soundings from the pair of coincident lines run at different speeds over the steep slope or other prominent topographic feature. Lines run in the same direction should be used so as to avoid the effect of pitch offset errors. The equation to compute time delay is:

$$TD = d_a / (v_h - v_l) \qquad \text{Eq. C-2}$$

where:
- TD is the time delay in seconds
- d_a is the along-track displacement
- v_h is the higher vessel speed
- v_l is the lower vessel speed

The survey lines are processed, plotted and compared while assuring that no corrections are made for positioning time delay, pitch error, roll error and gyro. The time delay is then averaged by getting several measurements of the displacement in the along-track direction. This process is performed iteratively until the profiles and contours match or achieve a minimum difference.

b. Pitch Offset Bias. The pitch offset bias is determined from the two pairs of reciprocal lines run over a slope at two different speeds. The important characteristic of pitch offset is that the along-track displacement caused by pitch offset is proportional to water depth. Thus, the deeper the water the larger the offset. The pitch offset can be computed using the following equation:

$$a = \tan^{-1} [(d_a /2) / (\text{depth})] \qquad \text{Eq. C-3}$$

where:
- a is the pitch offset
- d_a is the along-track displacement
- depth is the water depth

The lines are processed while only applying the positioning time delay correction and the static offsets of the sensors. The pitch offset is then averaged by taking several measurements of the displacement in the along-track direction. This process is performed iteratively until the profiles and contours match or reach a minimum difference. It should be noted that unless kinematic DGPS positioning is employed, determining d_a to a reasonable level of accuracy is difficult in shallow water.

c. Azimuthal Offset Bias. The same two pairs of lines run adjacent to a bathymetric feature will be used for the measurement of the azimuthal offset. One pair of adjacent lines run in opposite directions is processed at a time to remove any potential roll offset. The azimuthal offset can be obtained from the following equation:

$$y = \sin^{-1} [(d_a /2) / X_i] \qquad \text{Eq. C-4}$$

where:
- y is the azimuthal offset
- d_a is the along-track displacement
- X is the relative across track distance for beam i

The survey lines are processed with only the positioning time delay and pitch offset corrections and static sensor offsets. The azimuthal offset is averaged by several measurements of the displacement d_a over the feature and knowing the across-track distance X at the location of the measurements. This process is performed iteratively until the profiles and contours match or achieve a minimum difference.

d. Roll offset bias. Roll bias is computed using the pairs of reciprocal lines run over a flat, deep area. Generally this offset is the most critical in deeper water and should be carefully measured. For small angles of less than 3° the roll offset can be estimated by the following equation:

$$r = \tan^{-1} [(d_z/d_a) / 2] \qquad \text{Eq. C-5}$$

where:
- r is the roll offset
- d_z is the depth difference
- d_a is the across-track distance

The survey lines are processed while applying the positioning time delay, pitch offset, gyro offset corrections and static sensor offsets. The roll offset is averaged by several measurements of the across track displacement d_a along the test swaths. This process is performed iteratively until the profiles and contours match or achieve a minimum difference.

C-10. Performance Test. Quality assurance performance tests are conducted upon equipment installation or modification or at the beginning of major projects. This test partially checks the parameters and biases that were measured and computed during the above calibrations. The procedure described below compares a check line swath beam with a reference surface model complied from narrowly spaced multibeam data using only near-center beam data, or with single-beam data. It is not truly an independent test, only an assessment indicator. Failure of the performance test survey to meet the recommended tolerances in Tables A-1 and C-1 requires corrective action--i.e., remeasurement, recalibration, patch testing, etc.

a. Reference Surface. This is essentially a small survey run over a flat area in water depths of not more than 30 meters. It represents the "baseline" area. The beams outside about 45-60° swath width should be removed prior to editing. Four parallel lines are run with at least 150% bottom overlap--i.e., 25% sidelap. One should ensure that the inner beams overlap enough to give redundant data. After these lines are run, 4 or 5 parallel lines are run perpendicular to the previously run lines with the same swath and overlap. The speed over the ground should be the same on both sets of lines. A velocity cast should be made in this area and the corrections applied.

b. Check Lines. Multibeam "check lines" will be run such that the full beam array can be tested against the Reference Surface. A pair of parallel multibeam swath lines should be run inside the reference surface. Overlap as described above is not needed. The vessel speed is the same as for the reference surface.

c. Data Processing and Analysis. Performance test data processing should follow the general rules outlined below.

(1) The reference surface should be cleaned of outliers. This should be performed manually and adjustment of positions, attitude and bathymetry be made to ensure clean data. Smoothing, thinning, or binning of data must not be made.

(2) A digital terrain model (DTM) of the reference surface is created from the cleaned data. Then use an averaging gridding algorithm to smooth the data. The gridding size should be no larger than the average footprint of the inner beams or the estimated positional accuracy, whichever is greater. Using large vertical exaggeration, the DTM should be observed on 3D-visualization software.

(3) The check lines are then processed individually and each beam depth throughout the entire array is compared to the reference surface. A difference surface between the reference DTM surface and the check lines is then created and contoured and statistics computed to assess overall performance. From these differences the corrections to the system can be checked against the criteria recommended in Table C-1.

(4) Statistical parameters to be computed and evaluated include:

- Outliers. Depth differences between the check and reference surfaces are computed at each beam point along the check line array. Maximum outliers should not exceed the values recommended in Table C-1. Presence of excessive outliers in the outermost portions of the array indicates calibration/velocity problems, and requires correction and/or restricted beam widths.

- Mean Difference. The difference, or bias, between the reference and check surfaces should not exceed the recommended value in Table C-1. Excessive surface bias errors require immediate assessment and correction.

- Standard Deviation. The standard deviation (95%) of the differences between the reference and check surfaces should not exceed the limit shown in Table C-1--i.e., the prescribed performance accuracy standard for depths given in Table A-1. The existence of excessive outliers and biases will increase the overall standard deviation. Restriction of the beam array angle may reduce this error if most of the excessive outliers are in the outermost portion of the array. Results from this test may be used as an indicator of overall accuracy performance. In order to assess resultant accuracy as a function of swath width, it may be necessary to isolate sections of the beam swath.

C-11. Calibration and Quality Control Documentation. Project or contract files must contain documentary evidence that these calibration tests were performed. This would include a written log (or equivalent digital record) of sensor offset and alignment measurements, patch test calibration results, sound velocity measurements, tide/stage observations, performance test results, and other quality assurance observations, such as bar checks.

C-12. Multibeam Data Processing. Multibeam data is processed and edited on a variety of commercial platforms and software packages. Due to the size of the data sets, numerous thinning or binning methods exist for reducing the data down to manageable levels. The procedures used for such data thinning/binning may adversely corrupt or erroneously warp the reduced model, and could impact dredged volume computations. This could occur if shoal biasing or averaging is used to form a digital terrain model (DTM), digital elevation model (DEM), or triangulated irregular network (TIN)--such biasing processes should be avoided.

C-13. Summary. The above measurement, alignment, calibration tests, and quality assurance procedures are based on procedures currently followed by a variety of government and commercial sources, such as those listed in the reference paragraph. Many of these procedures, and related intelligent data thinning software routines, are being continually updated as new algorithms and performance test techniques become validated. Maintain contact with CETEC-TD-G for updates on current developments.

Table C-1. Recommended Multibeam Calibration Procedures and Criteria

	Frequency of Measurement (Minimum) [1]	Calibration Procedure	Allowable Tolerance (95%)	Corrective Action
SENSOR ALIGNMENT AND OFFSET MEASUREMENTS:				
Transducer	Initial installation	Leveling/Tot Station	0.5 degrees	Remount
Gyro	Initial installation	Self calibration	Manufacturer's specification	Replace
Heave/Pitch/Roll	Start of project	Self calibration	0.1 degree	Remount
GPS Antenna	Initial installation	Leveling	0.1 foot	Remount
Squat	Annually	Transit/level/DGPS	0.1 foot	None
Dynamic Draft	As required	Fixed vessel marks	0.1 foot	None
ACOUSTIC DRAFT AND SOUND VELOCITY MEASUREMENTS:				
Bar Check	Twice daily	Bar ck center beam	0.2 foot	Stop/redo
Velocity Probe	Twice daily or more	Self calibration if conditions require	0.01 m/sec	stop/redo
PATCH TEST (RESIDUAL BIAS CALIBRATION):				
Pitch	Init Install or Mod	2 pairs or reciprocal lines on slope	0.2 feet	apply corr'n in software
Roll	Init Install or Mod	1 pair of reciprocal lines over flat area	0.2 feet	apply corr'n in software
Time Delay (latency)	Init Install or Mod	2 pairs of reciprocal lines on slope	0.2 feet	apply corr'n in software
Azimuth/Yaw	Init Install or Mod	2 pairs of adjacent lines over shoal	0.2 feet	apply corr'n in software
PERFORMANCE TEST (QUALITY ASSURANCE TEST):				
Mean Bias	Start of Major Proj	Run Reference & Check Surfaces	0.2 feet	redo prior calibrations
Standard Error	Start of Major Proj	Run Reference & Check Surfaces	per Table A-1	redo prior calibrations
Maximum Outliers	Start of Major Proj	Run Reference & Check	1 foot	Reduce array

1. Calibration frequency indicated should not be considered absolute as it is subject to local conditions, such as stability of project area, stability between repeated tests, nature of project, etc.

Table C-2. Summary of Patch Test Procedures and Computations

	Posit/Time Delay	Pitch Offset	Azimuth Offset	Roll Offset
LINES REQUIRED	Two (2) on same heading over slope or shoal	Two (2) pairs on reciprocal headings at 2 speeds	Two (2) pairs over bathymetric feature	Two reciprocal lines over flat area
PRIOR CORRECTIONS APPLIED	None--other than static offsets	Positioning time delay	Position time delay and pitch	Position time delay, pitch, &gyro
COMPUTATION METHOD	Average of displacements in along track direction	Average of displacements in along track direction	Average of displace in across track direction	Average of displacements in across track direction
VISUAL METHOD	Match profiles and contours	Match profiles and contours	Match profiles and contours	Match profiles and contours